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14. ABSTRACT Using ultrasound as a detection device in the body, including the brain, has been extensively investigated. Unfortunately, previous ultrasound-based methods in the brain have suffered from the severe distortion caused by the skull bone. However, we have recently developed a technique that allows ultrasound to propagate through the skull with significantly reduced distortion, using a shear mode technique. *The current project will develop a device for non-invasive identification of the presence of foreign bodies inside the skull*, and localization of such objects within the skull, will be lightweight, portable, durable, battery-operated, easy to use and appropriate for effective and practical battlefield use in forward areas. The finished device will operate in two modes: In the first mode it will function as a hand-held device, powered by AA batteries. In this mode it will provide a simple yes/no indication on the presence of foreign bodies as a function of location in the brain. In the second mode, the same device will also be capable of interfacing with laptop computer via USB interface. In this mode imaging and analysis software will form an image of regions in the brain, which can be interpreted by a medic or relayed to a remote medical professional for evaluation.

15. SUBJECT TERMS
Ultrasound, Portable Diagnostic Device, Brain Monitoring

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Portable Ultrasound Brain Imager (SMTUS): Progress Report

A prototype ultrasound device to test for optimized data acquisition parameters for the proposed device has been designed, constructed, characterized, and tested. The portable ultrasound brain imager (SMTUS) incorporates four novel design aspects to achieve efficacy: (1) a focused ultrasound transducer with a pressure field profile that selectively monitors specific intracranial regions; (2) a lowered effective ultrasound frequency (f_c = 0.84 MHz) to overcome attenuation stemming from the skull bone; (3) shear-mode transmission through the skull bone to enhance energy transmission and reduce beam aberration; and (4) a low ultrasound duty-cycle for time-extended application.

From the results of preliminary studies, it was observed that the intracranial monitoring depth of the SMTUS suffered from low signal-to-noise ratio (SNR) after a depth of approximately 40 mm into the cranial vault (9.6 dB at 40 mm). A series of experiments were performed to improve the depth at which useful signals could be obtained. Ex vivo calvarium specimens (24 data points over 3 calvaria) were used to examine the effects of lowering the operating frequency of the SMTUS. Results showed that a change of ultrasound insonation frequency from 1.0 MHz to 0.84 MHz significantly increased the overall SNR (+17.5 dB) and in effect, increased the monitoring depth by approximately 60 mm (from 40 mm to 100 mm) (Fig. 1). The monitoring depth is defined as that which yields an SNR on the order of an MR T_1-weighted image (3 Tesla, SE, TR = 650 ms, TE = 10 ms). So, the actual depth at which the SMTUS could effectively operate is higher than the given numbers, only with increasing depth, the SNR decreases exponentially.

SMTUS development continued with the creation of an intraoperative user interface that would allow the real-time identification and tracking of intracranial structures and shifts at high temporal and spatial resolutions (Fig. 2). Specialized data acquisition hardware along with an algorithm that would process raw backscattered ultrasound data with optimized efficiency were needed for real-time application. An Intel-based (Intel, Core2 Duo, 789 MHz, Santa Clara, California, USA) laptop computer (Dell, Latitude E5500, Austin, Texas, USA) operating with a high-speed USB-GPIB controller (National Instruments, Austin, Texas, USA) for signal acquisition was used to acquire time traces of the SMTUS's backscattered signal at a sampling rate of 40 MHz (1×10^4 samples over 250 μs), resulting in a time trace acquisition rate of approximately 2 Hz.

To allow for the identification and tracking of backscattered signals stemming from hyperechoic structures within the cranial vault, the SMTUS signal was processed according to

$$K(t) = H\left(\left(I(t) - I_B(t)\right) \otimes \left(e^{-t^2/2\sigma^2}\sin\left(2\pi t\right)\right)\right)e^{\alpha f d}, \qquad (1)$$

where $I(t)$ is the SMTUS backscattered pressure, $I_B(t)$ is the SMTUS baseline data, t is the time vector corresponding to the recorded data, σ is the standard deviation of the Gaussian function that is related to the fractional bandwidth of the modulated sinusoid, ⊗ represents a cross-correlation performed in Fourier space, H is the Hilbert transform, α is the tabulated attenuation coefficient for brain tissue, f is the insonation frequency, and d is the propagation distance. The resulting time trace as converted to a distance trace is displayed in the center panel of the user interface (Fig. 2). The resulting signal has identifiable peaks that correspond to backscatter sites within the cranial vault. The user can then manually select a range of distances to track any given peak in the signal. The results from peak tracking are displayed and continuously updated in a separate panel of the user interface (Fig. 2). To allow for more flexibility in structural identification and monitoring, distance- and amplitude-static fiducials can also be added within the backscattered time trace without interrupting continuous operation of the SMTUS.

For testing and validation studies, hardware was designed and constructed to allow for the integration of the SMTUS with a neurosurgical navigation platform (BrainLab, Feldkirchen, Germany). An attachment to the SMTUS prototype was designed and constructed to mount a rigid needle that is spatially matched to the ultrasound trajectory (Fig. 3). This needle, which represents the virtual vector of the SMTUS imaging trajectory, could then be registered to MR imagery through the neurosurgical navigation system. This capability will allow for future validation studies with human subjects.

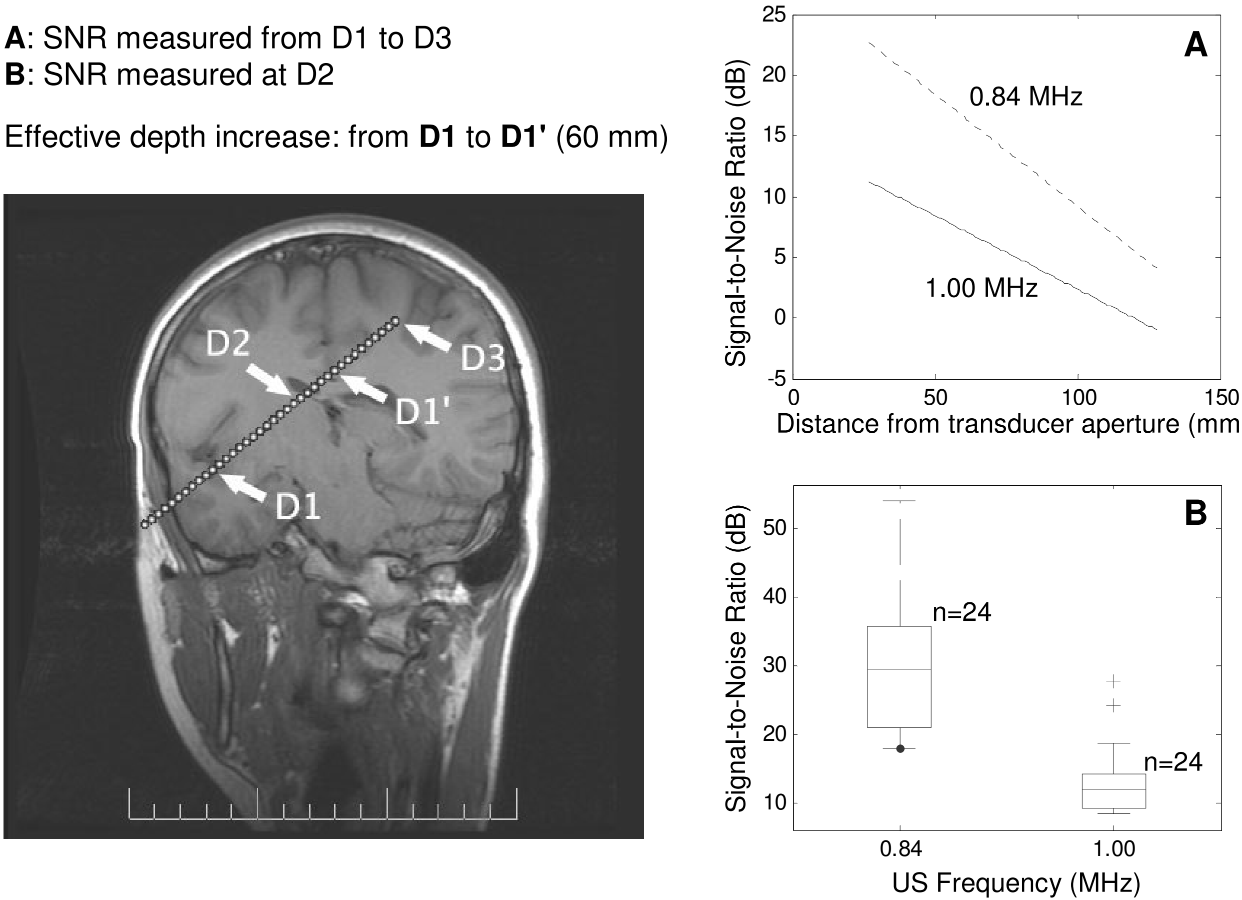

Figure 1. The SNR of backscattered signals of the SMTUS operating at 1.00 MHz and 0.84 MHz are shown (A) with respect to distance along the SMTUS propagation axis and (B) measured over a plane orthogonal to the SMTUS propagation axis. The MR image is overlain with the SMTUS propagation path to give approximate indication of the effects of reducing the SMTUS insonation frequency.

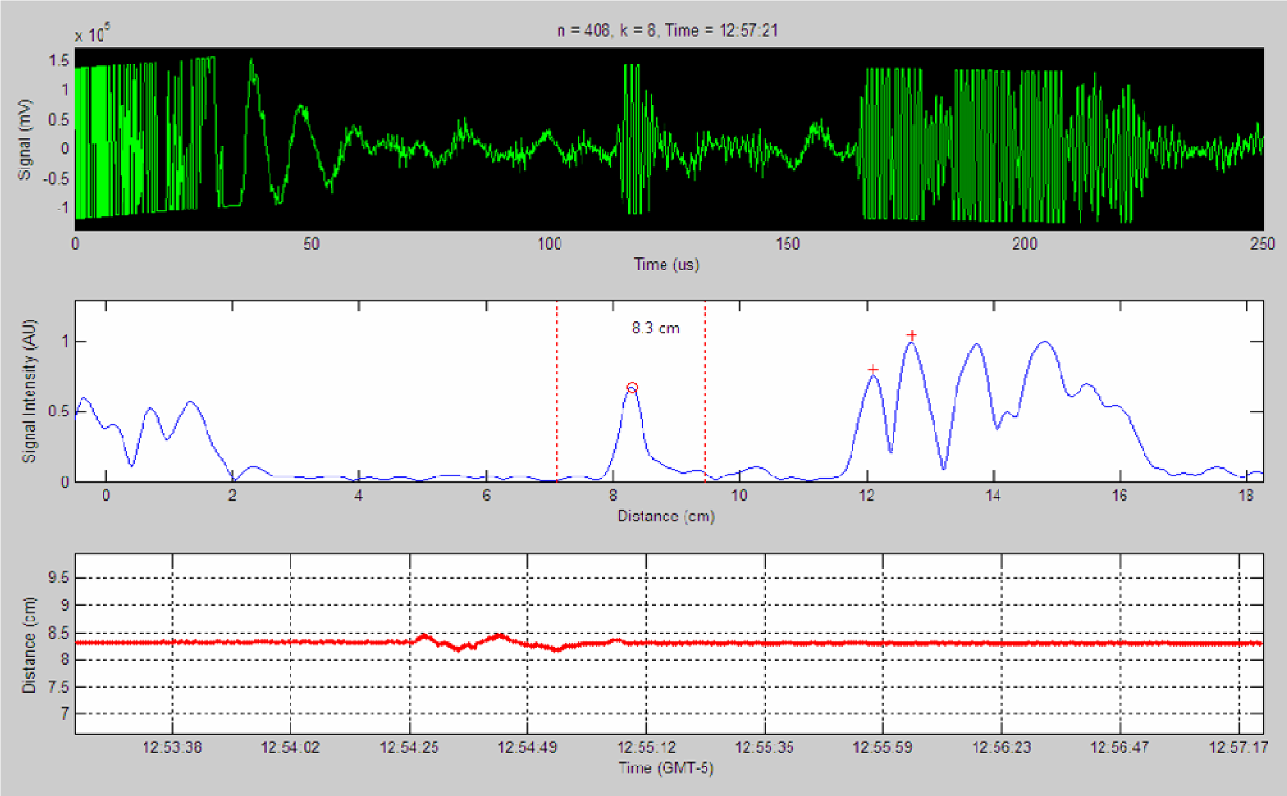

Figure 2. A screen shot from the SMTUS user interface: (*Top*) the raw backscattered signal; (*Center*) the processed "A-line" with a tracking range delineated by vertical red lines, a red circle marking the tracked peak and labeled with the distance from the SMTUS aperture, and red crosses indicating spatially-static fiducials; and (*bottom*) continuously updated plot of the tracked backscatter peak from the center panel. The system displays and records time traces at a rate of approximately 2 Hz.

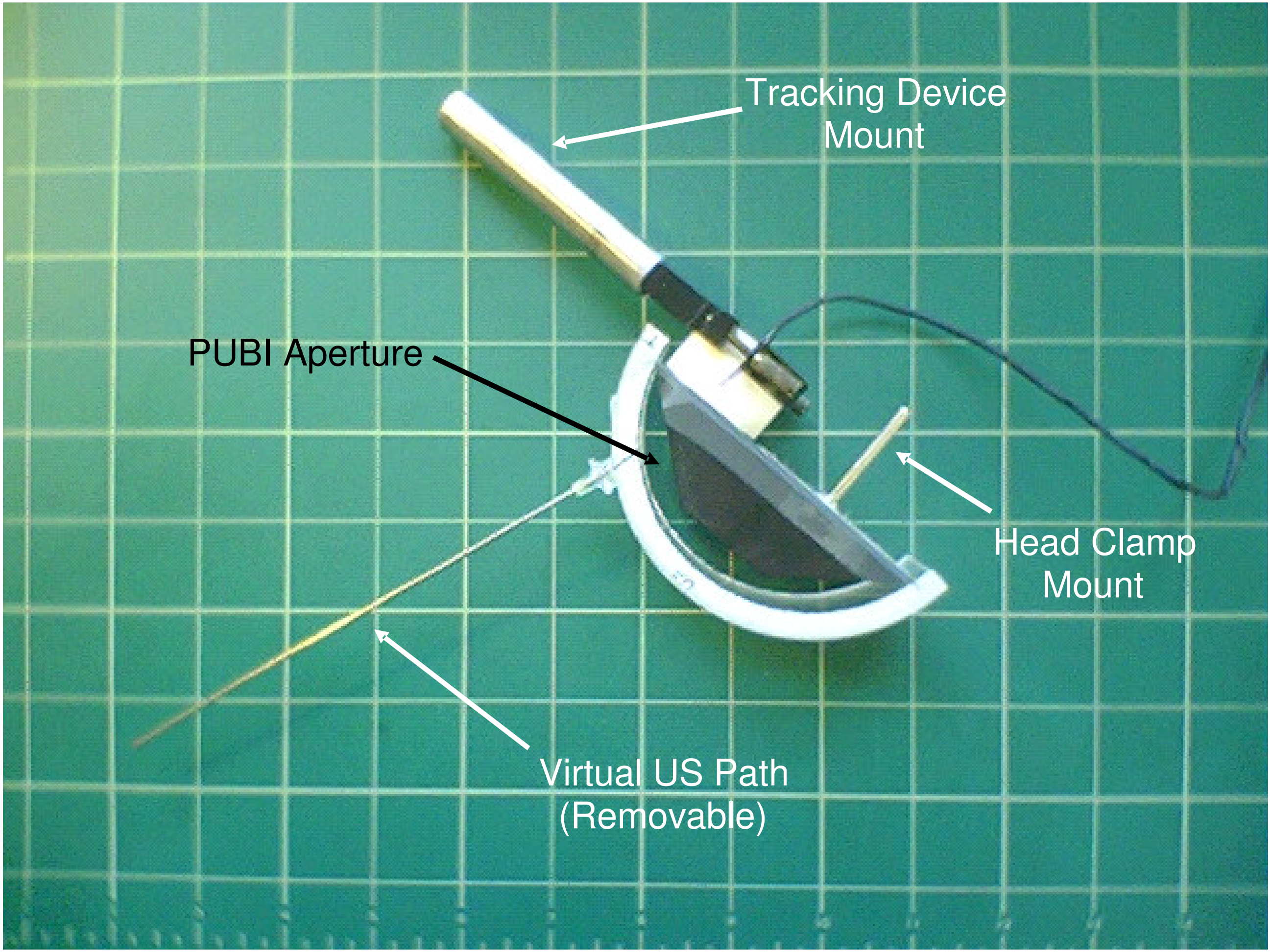

Figure 3. A photograph of the prototype SMTUS (divisions = 2.54 cm)